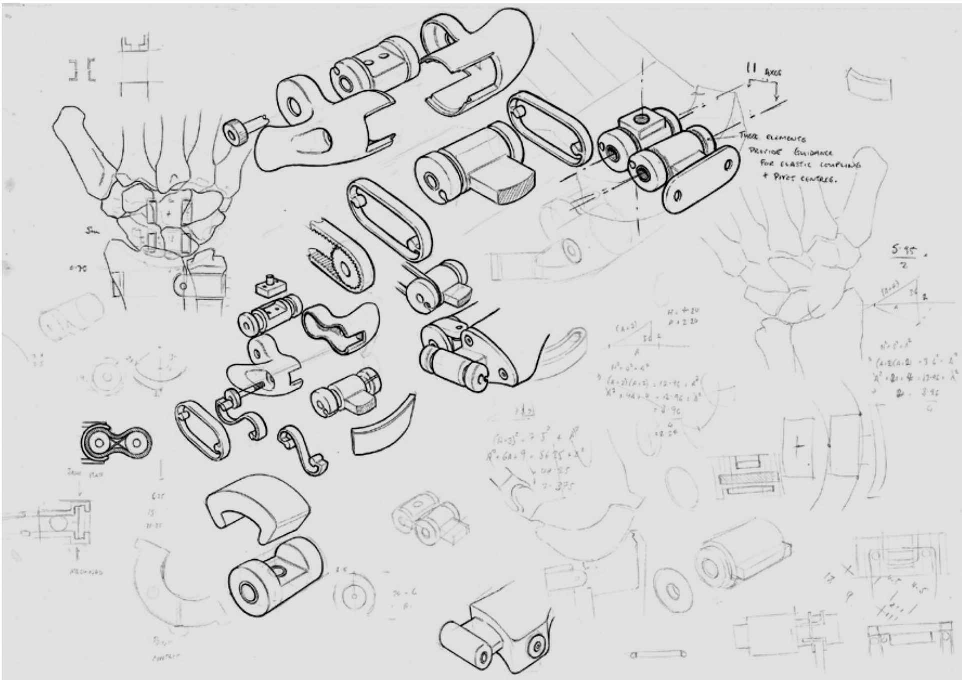
7. Development of an Anatomically Analogous Wrist Joint and the Evaluation of the Skeletal Model Arm



A Sketch Sheet in the Development of the Model Wrist

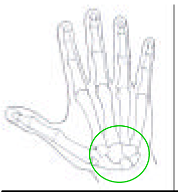
To complete the model limb to mid humeral level for further evaluation it was considered that another wrist design was necessary that could be used to connect the previously developed hand to the model arm.

The initial wrist design was developed as part of the hand model principally to serve as a tool for the evaluation of the finger joints. The first model wrist was not developed using the same creative reasoning processes that had been used in the development of the model finger joints. It was found that the model wrist appeared less successful than some of the design principles embodied in the model finger joints, indicating that a second wrist model developed using creative reasoning processes may be more successful.

This chapter starts with a comparison of the articulations of prosthetic wrists and those of the human wrist. It then details the initial sketch book idea development that was completed trying to match the articulations of the wrist using principles elucidated in the development of the MCP joint. Conclusions form this exercise are then presented with Dr. Williams's evaluation of the first wrist (evaluations -chapter 4) to shown how this led to the next cycle of creative reasoning.

This is followed by a description of how model making and measurements taken from the intact wrist formed additoinal inputs into the creative reasoning process. The generation of a final design also highlights the extensive use of CAD / CAM techniques in the production of a complex form with a complex embedded mechanism.

As was the wrist was the final component necessary to link the model hand and arm this chapter finishes with the evaluation of the whole model arm including the wrist.



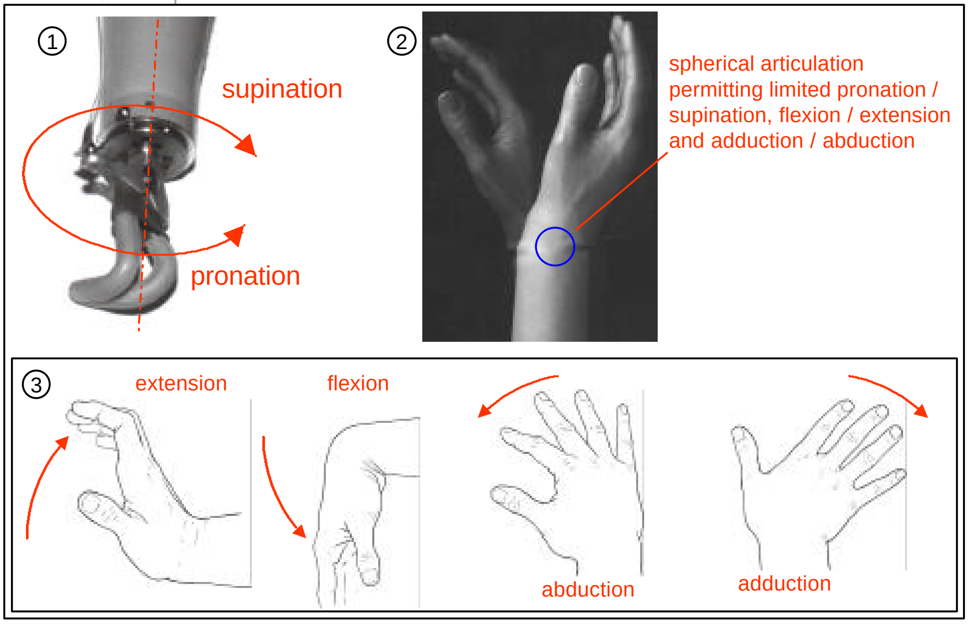


Fig 7.1 Prosthetic wrists and movements of the Human Wrist

As described in the forearm section (prosthetic components - chapter 5) prosthetic wrist components commonly only provide pronation / supination movements (1). However, the human wrist possess articulations for adduction / abduction and flexion extension movements (3) whilst movement of the whole of the forearm provides pronation and supination at the wrist (fig 5.2 (1,2)). Figure 7.1 (2) shows a passive fiction wrist available from Vessa Ltd. (No. 0010 Vessa Multiaxial Wrist Housing), that provides all three degrees of rotational freedom at the wrist. This component is only for the unilateral amputee as it must be positioned by the contralateral hand. The articulating mechanism used in this wrist can only provide part of the range of movement of the normal human wrist and is unlike the structure of the human wrist.

Evidence has shown (evaluation - chapter 4) that the absence of movement in the wrist section of a prosthesis is key in betraying the limbs artificiality. Therefore, it was deemed appropriate to devise articulations that were able to closely replicate the movement of the human wrist joint.

The wrist joint of the first model hand was quickly developed to enable a whole hand form to be created, principally for evaluation of the finger joints. During the development of the first wrist, measurements were taken to estimate the width of the wrist, and it's centres of rotation in flexion / extension, adduction / abduction. This was done by palpating the wrists of the researcher. From the palpation, marks were placed on the skin where visually it appeared that the centres of rotation occurred. The hand was photocopied to provide a two dimensional underlay from which an elementary articulated wrist was developed. Ranges of movement were visually assessed and appropriate stops placed in the mechanical design of the wrist.

The concepts that had been deduced from the observational drawing and sketchbook development of the IP joints were transferred to the mechanical design of the wrist. Like the IP joints, rotations were considered to occur about a single centre, and so simple hinge joints were made (translation of joint principles - chapter 4).

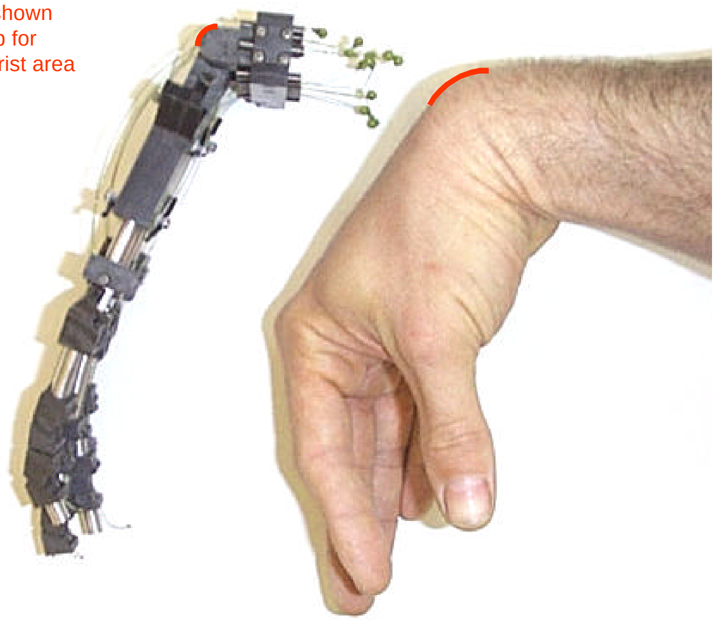


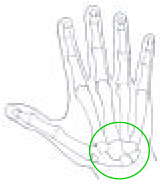
Fig 7.2 Flexion of the Human Wrist and the First Model Wrist

The evaluation of the prototype first model wrist identified several areas where the model wrist appeared to not to be a close analogy to the human wrist (evaluation - chapter 4).

The model wrist was palpated in the plane of flexion / extension by the researcher and compared to the palpated movement of a human wrist. This process highlighted a different 'quality' to the movement of the human wrist. It was also observed that the radius of curvature of the dorsal surface of the model wrist appeared to be different from that of the human wrist. The human wrist possesses a curvature with a much larger radius than that of the model for a similar angle of flexion. This didn't appear to be completely explained by the depth of the skeletal wrist components within the human hand (figure 7.2).

Observations from experiments using the pretensioning rig (evaluation - chapter 4) identified problems at the wrist when the model wire tendons were pretensioned. It was found that the movement of these tendons across the centre of rotation on the wrist in the plane of adduction / abduction resulted in an unstable wrist. Where the wrist would not remain in a neutral position, instead, tending either to latch towards maximal adduction or abduction.

Additionally, the attachment of analogous tendons for the digits highlighted coupling problems associated with flexion and extension movements of the wrist. It was found that extension of the model wrist effectively shortened the flexion tendons to the digits, consequently flexing the fingers. The reverse was found to occur in flexion of the wrist.



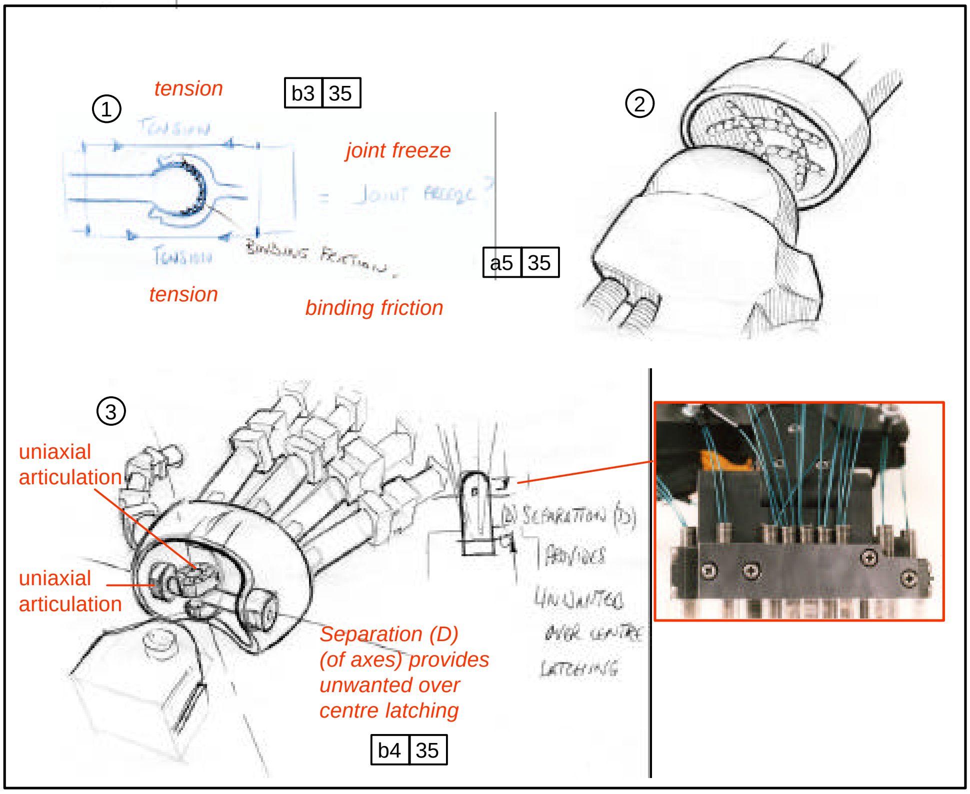


Fig 7.3 Wrist Sketches Using Principles from MCP Joint Development

Initially, for the second wrist design joint principles that had been identified in the development of the MCP joint were considered to solve some of the problems highlighted in the evaluation (evaluation - chapter 4)
To address the problem of the tendency of the model wrist to latch, ideas were considered that unified the centres of rotation of the model wrist in the planes of flexion / extension and adduction / abduction. Eliminating the distance between the centres of rotation would mean that the tendon guides could be much closer to them both . Therefore the analogous tendons would not be able to translate across the joint centre, which had been identified as the major cause of latching.
Sketch (1) shows a spherical design. Like early sketches in the development of the MCP joint this was considered as it possesses a single centre of rotation yet it can be configured to permit only two degrees of freedom.
Initially, materials such as bearing plastic for the cup and socket were considered for prototyping this joint (1). However, it was thought that due to the number of tensioned analogous tendons running across the joint in combination with the large surface areas in contact this joint might have a tendency to bind or display a 'jerky' movement due to friction in a plain bearing of this size (1). Therefore, to reduce the areas of contact, rows of ball bearings were sketched within the socket. However, a constrained path for these ball bearings that also allowed fiction free wrist movement could not be adequately resolved (2).
Again to minimise surfaces areas in contact, universal joint ideas were sketched, similar to those sketched in the development of the MCP joint. These depict orthogonally placed uniaxial joints running on frictionless roller bearings (3).

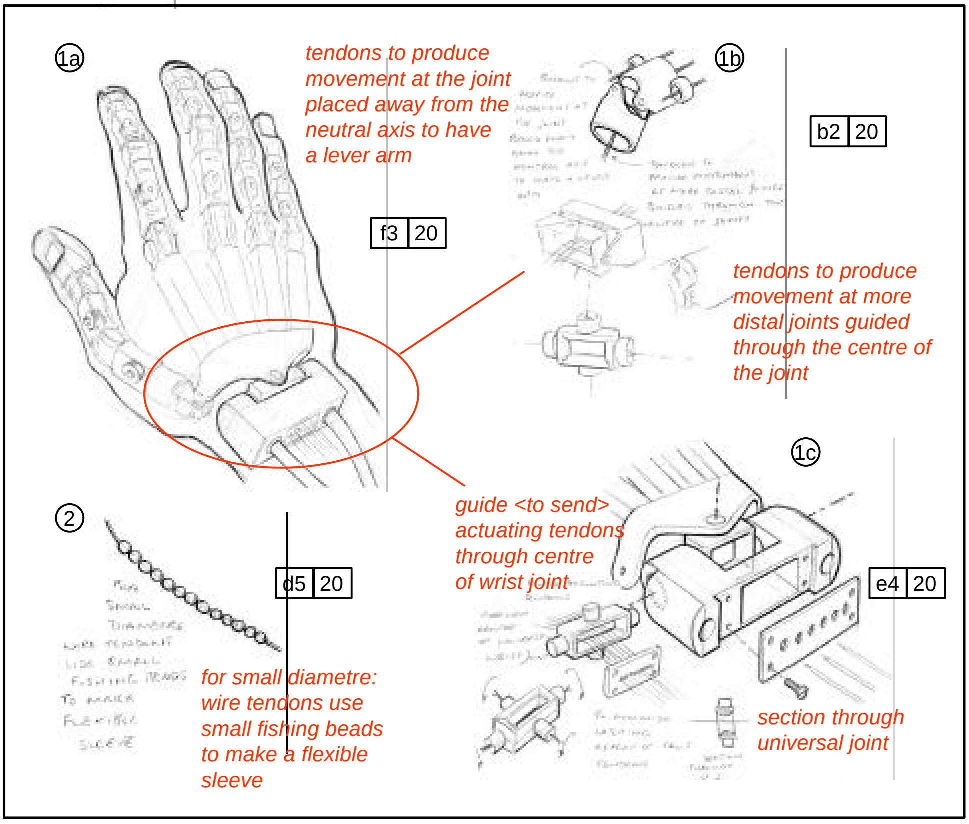
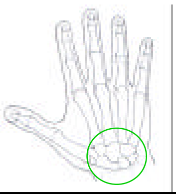


Fig 7.4 Sketch Ideas for Wrist limiting Coupling

The previous ideas appeared only a partial solution to the problems of the first model wrist. Examination of the first model wrist within the tendon test-rig had showed that movement of the wrist joint produced undesired movements of the fingers, due to the mechanical coupling of the wrist to the finger by the analogies of the extrinsic to flexor / extensor tendons (evaluation - chapter 4).

Subsequent sketch ideas were produced that expanded on the universal joint ideas previously developed. The universal joint was sketched as a hollow design (1 a-c) which would guide the extrinsic tendons as closely as possible through its centres of rotation. It was considered that if the extrinsic tendons could pass as close to the centres of rotation as possible the effect of wrist position on finger position would be minimised.

Other ideas to minimise mechanical wrist-finger coupling included guiding analogous extrinsic tendons around the wrist using Bowden cables. However, it was found that commerically available Bowden cables were unsuitable for passage around the tight radii produced by a flexed wrist due to bending of the close wound metal springs within the sleeve of the cable. Ideas for sleeve designs capable of passage around such tight radii were considered using small fishing beads (2). However, simple tests showed that this arrangement produced too much friction when the cable was tensioned within the beads.



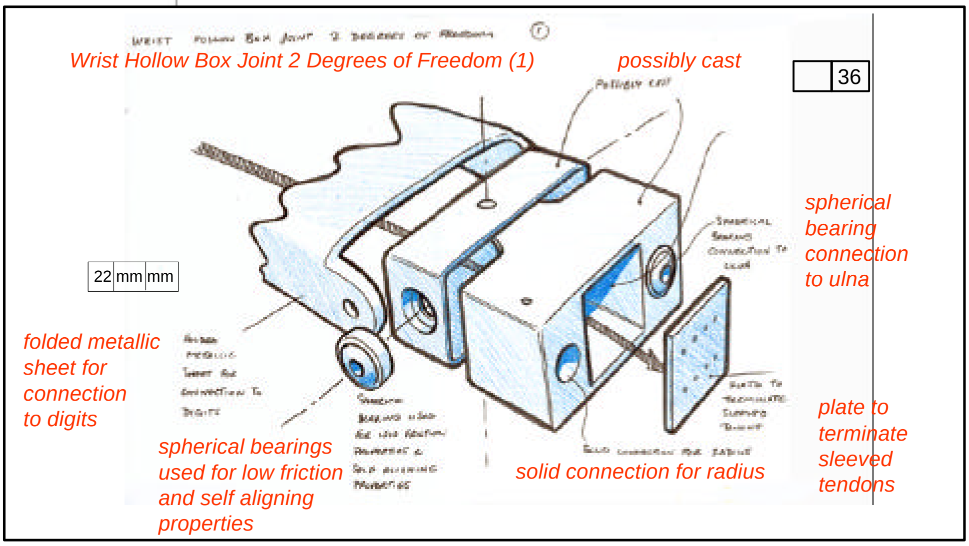


Fig 7.5 Sketch Idea for a Mechanical Solution to Wrist - Finger Coupling

The previous sketch ideas were not considered ideal solutions to the coupling problems. Guiding the tendons as close to the centre of a hollow universal joint was considered the more favourable, however, friction problems were foreseen with cables rubbing against one another.

Review of the first model wrist by hand surgeon Dr. N. Williams, highlighted that the guidance of the tendons around the model wrist did not represent a close analogy of the human anatomy. He considered that the guidance channels in the model were too proximal and that the carpal tunnel and extensor retiniculi that guide the extrinsic tendons around the wrist needed to be much closer to the centres of rotation of the wrist joint (evaluation -chapter 6). Dr. Williams comments also indicated that further observation may point to mechanical refinements of the guidance of the tendons though the wrist to lessen latching in the plane of adduction / abduction. However, as the tendons do not pass through the centre of the human wrist in the plane of flexion and extension (Armstrong and Chaffin 1978) it was unclear how a close mechanical analogy of the human wrist could eliminate undesired movements of the fingers caused by movement of the wrist.

Reference to anatomical literature (Fox 1993) showed that the independent movement of the wrist and the fingers, despite their extrinsic tendon coupling, was managed through low level nervous system interconnections made through the spinal cord (Fox 1993). These interconnections enable the extrinsic agonist and antagonist muscles responsible for finger movement to compensate for movements of the wrist (Armstrong and Chaffin 1978). Consequently, it was considered that a mechanical solution to the coupling problem might not be appropriate. A review of advanced robotics literature indicated research into possible actuator control strategies that might permit a control system analogy of the nervous system connections of the human body (Hannaford et al 1995).

The early wrist sketch ideas showed that a mechanical design may not be able to solve all of the coupling difficulties of the first model wrist. However, it was thought that further observational drawing studies were required to inform the next cycle of wrist joint design. It was anticipated that observational drawing might elucidate more subtle kinematic principles that could be used in the next wrist design.

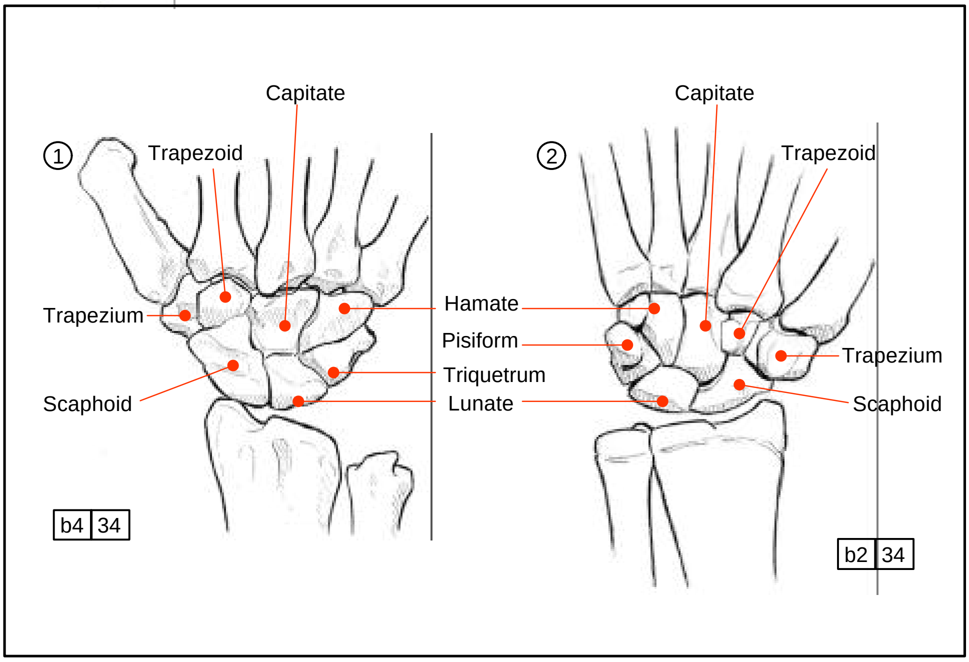


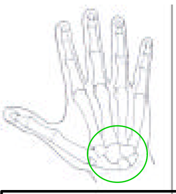
Fig 7.6 Observational Drawings of the Human Wrist

Observational drawings were produced of the human wrist from an anatomical skeletal model arm to gain an understanding of the three-dimensional form of this joint. The figures above show dorsal (1) (palm down) and volar (palm up) (2) views of the skeleton of the human wrist.

It can be seen that the human wrist is composed of numerous small bones called carpal bones. These bones are formed so that they can move relative to one another (Berger et al 1982) and in the intact human arm they are connected together by numerous ligaments (Youm and Flatt 1982). The form of the carpal bones is such that in the neutral position the fit between the bones is highly congruent allowing relatively large loads to be supported by the wrist (Kapandji 1982).

As the following pages will include a discussion of the boney anatomy of the wrist it is appropriate to become familiar with this nomenclature.

The labels of the carpal bones reflects the form of these bones. Carpal is derived from carpus indicating that the wrist is divided into many pieces (Lewis and Short 1962.). The individual names of the carpal bones are also descriptive of their form. The carpal bone at the base of the thumb, the trapezium indicates that it has a roughly quadrilateral shape with two sides parallel (Lewis and Short 1962). The neighbouring trapezoid carpal indicates that it is of quadrilateral shape with no sides parallel. The label capitate indicates that this bone possess a large 'head' (Lewis and Short 1962). The hamate carpal is derived from the Latin - hook and alludes to its hooked form (Lewis and Short 1962) that provides part of the support for the 'carpal tunnel' (Kapandji1982). The scaphoid carpal is derived from the Latin for vessel or boat (Lewis and Short 1962), and describes the concave and convex elements of this bone. The title lunate describes the crescent moon shape of this bone. The carpal labelled triquetral described the three sided form of this bone (Lewis and Short 1962), whilst the label pisiform indicates that this bone is of round and of a small size (Lewis and Short 1962).



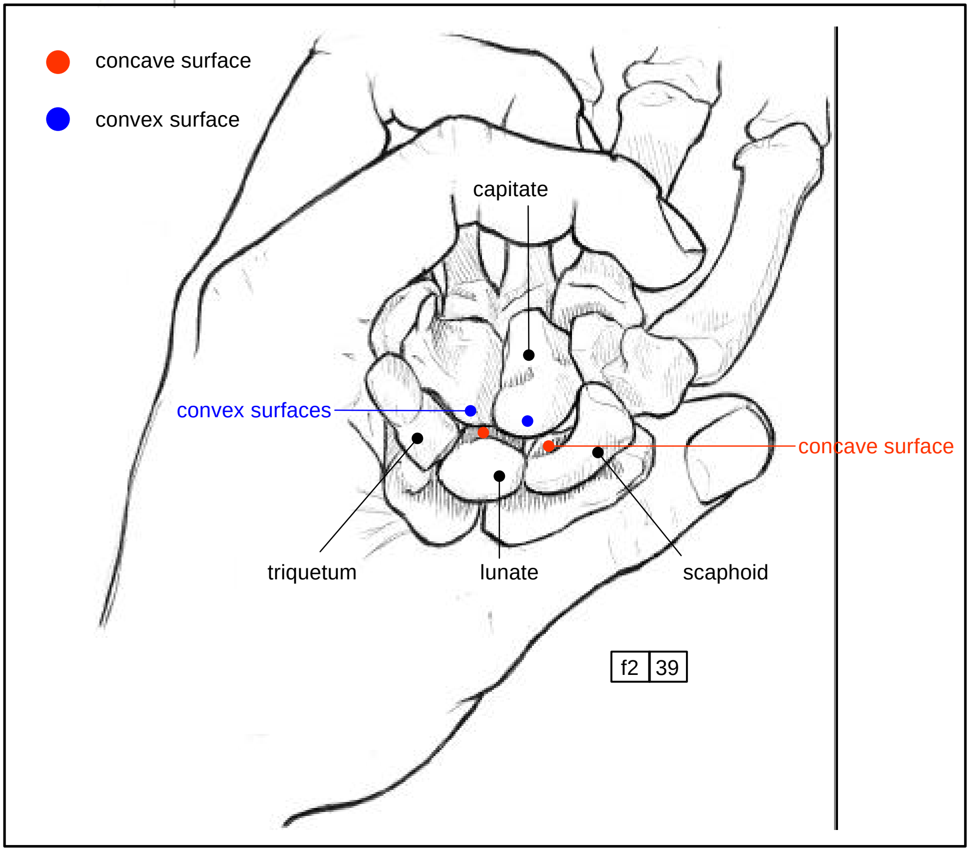


Fig 7.7 Observational drawing of the Midcarpal Joint

Observational drawing highlighted several areas on the carpal bones that were smooth and appeared to possess portions of simple geometric forms, such as partial spheres and cylinders. It was reasoned that these may indicate possible articulating surfaces. Such surfaces were observed on the head of the capitate and hamate, and that these appeared to be part of a line of articulating surfaces, transversely dividing the carpal bones into two rows.

Further observational drawing was performed with the skeletal wrist 'hyperextended' to reveal the form of the articulating surfaces between the two rows of carpals. The exercise showed that the convex head of the capitate rotates with a concavity of the lunate. Additionally, it showed that the capitate similarly rotated within the saphoid, whilst towards the thumb side of the saphoid, the saphoid itself presented a convex face for rotation within the trapezium. This appeared mirrored on the triquetral side with the hamate presenting a convex face to the lunate and part of the triquetral, then reversing, so the triquetral presents a convex face to the hamate.

It was considered that further literature review was required to verify the presence of a mid-carpal articulation during actions of the intact wrist.

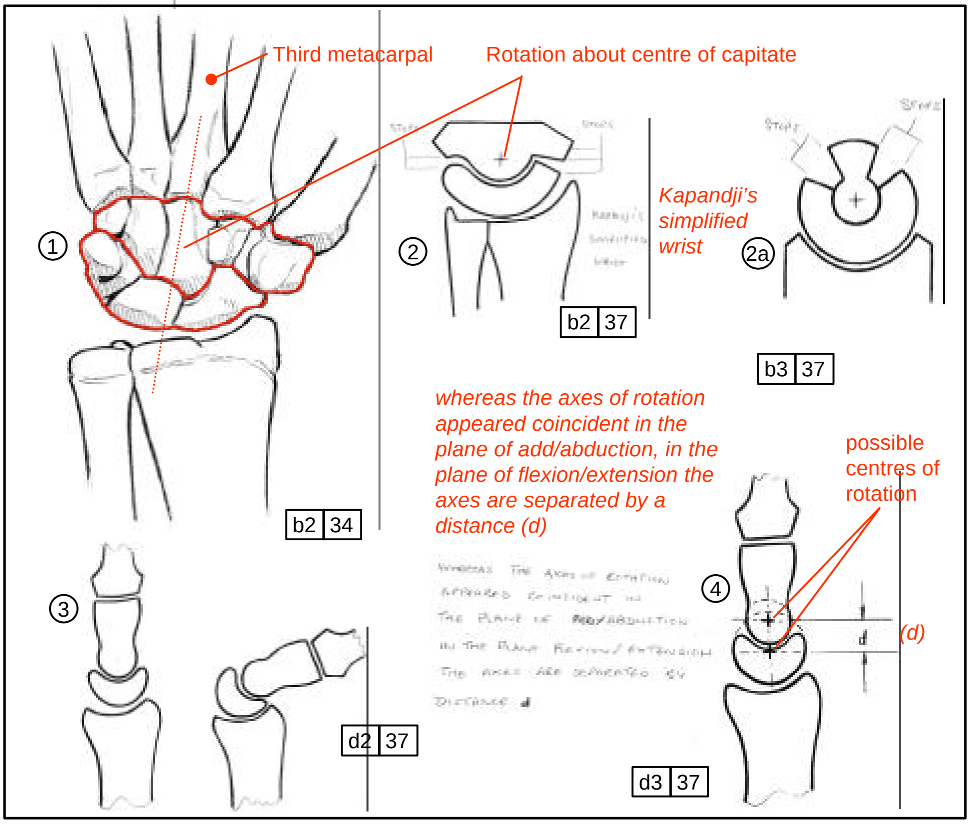
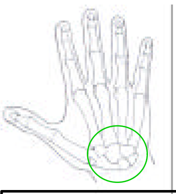


Fig 7.8 Articulations of the Wrist

The literature review indicated that two theories have been put forward for the action of the carpal bones within the intact wrist. One theory attaches significance to a 'rigid' the connection of the lunate, capitate and third metacarpal. This is referred to as the 'capitate column' theory, where little transverse movement occurs between these bones to provide maximum stability to the third metacarpal (Berger et al 1982). The second theory divides the carpal bones into distal and proximal rows (Kapandji 1982). The distal row includes the trapezium, trapezoid, capitate and hamate, whilst the proximal row includes the triquetral, lunate and scaphoid (Kapandji 1982) (1). During flexion / extension and adduction / abduction movements of the wrist it is stated that the distal and proximal rows of carpal bones rotate relative to one another (Kapandji 1982). From observational drawing studies of the articulating surfaces between the capitate and lunate it appeared that the form of these bones would allow movement rather than stop it. Therefore, the carpal row theory was followed as the carpal column theory supports no movement between these carpals.

Simplified drawings produced by Kapandji were reproduced (2), and further 'mechanised' (2a). Figure 7.7(2) shows Kapandji's contention that adduction and abduction movements of the wrist occur about a point approximately at the centre of the head of the capitate (Kapandji 1982). The distal carpal row rotates relatively to the proximal row, however, the rows have roughly concentric articulating surfaces resulting in rotations about a single centre (2a). During flexion and extension of the wrist Kapandji states that rotations occur between the distal and proximal carpal rows, as can be seen in the cross sections (3). A simplified cross section (4) shows how if the articulating surfaces are considered to be radii of circles then this motion might be considered as occurring between to separate distinct centres.



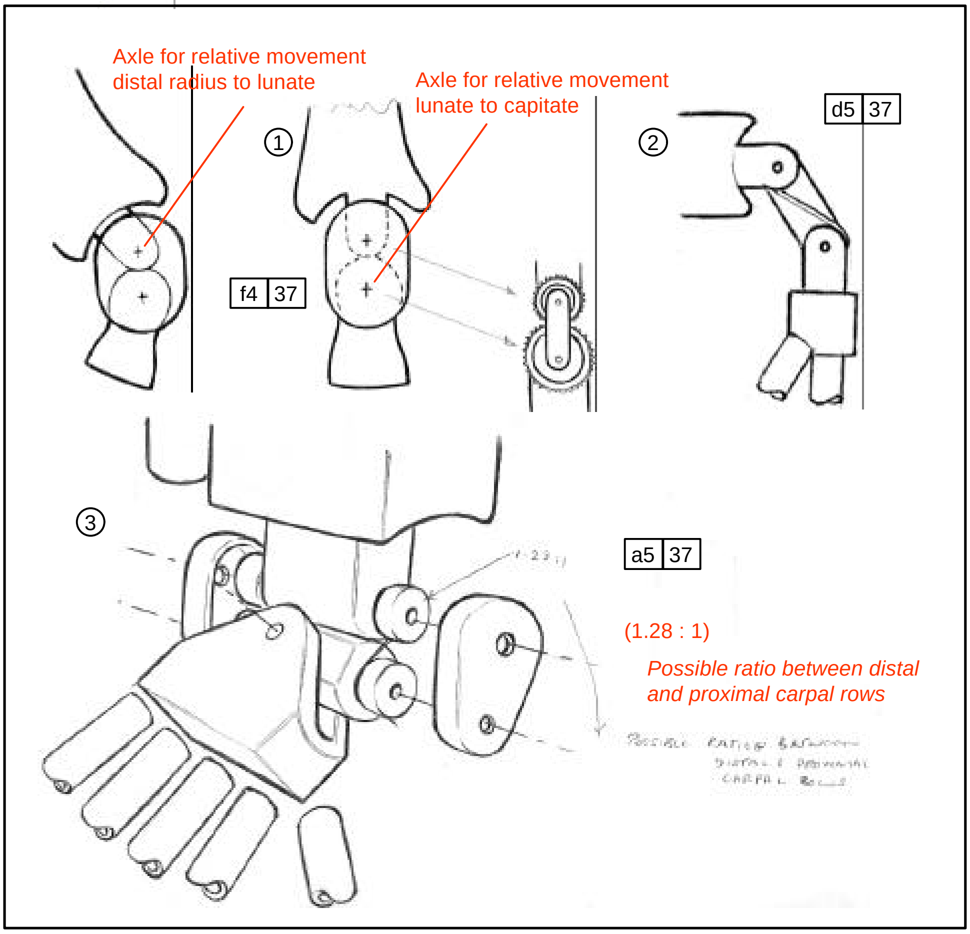


Fig 7.9 Sketches for Distal and Proximal Carpal Row Wrists

Focussing on the articulation of the wrist in flexion and extension; several means of coupling analogous distal and proximal rows were sketched. Based on the simplified cross section shown in figure 7.8 (4).

Initial sketches explored the use of gear teeth to connect the axles (1). Whilst sketches (2) and (3) explored connecting the axles using a pulley belt.

From literature review an approximate ratio of 1.28:1 was determined as the ratio between movement of the capitate to lunate compared to the movement of the lunate to the distal head of the radius during flexion and extension movements (Berger et al 1982). To achieve a similar ratio between the axles different sized gears and pulley wheels were considered. This approach was subsequently rejected as it was thought that a serrated gear would not be an appropriate surface for analogous tendons to run over. Consequently, further sketch book development centred on a pulley connection.

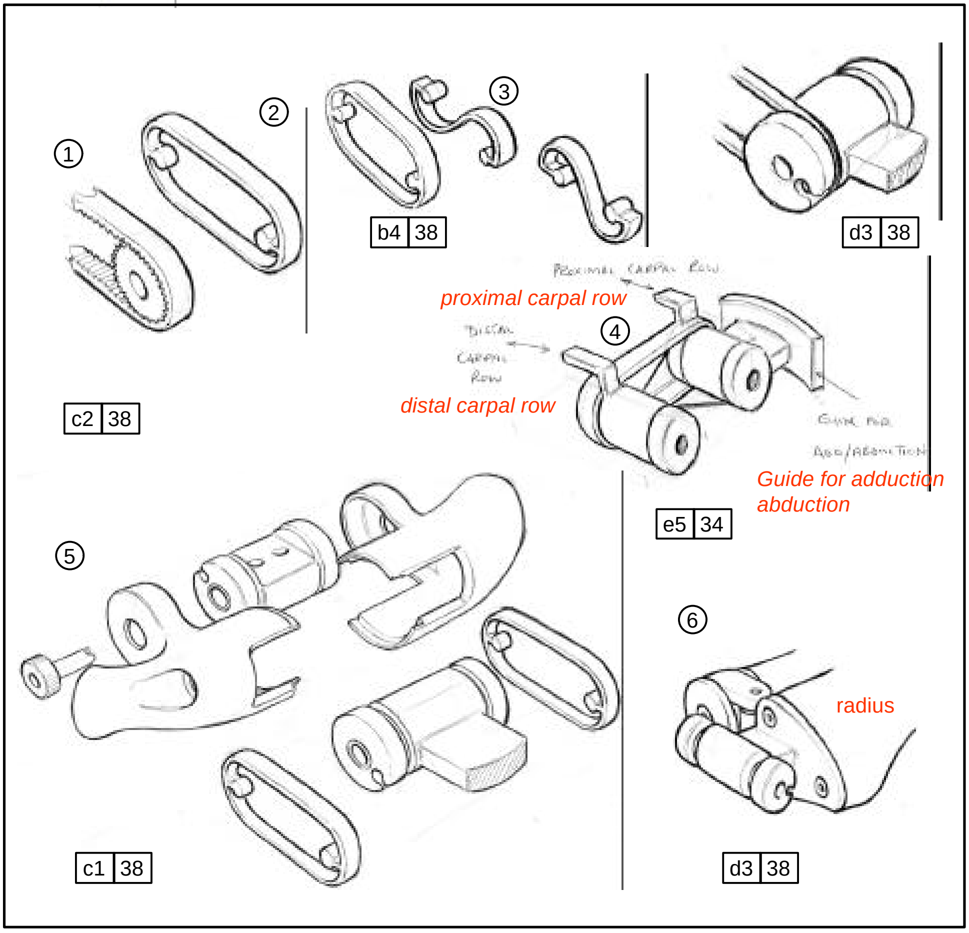
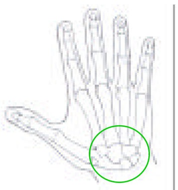


Fig 7.10 Sketches for Distal and Proximal Row Coupled by Pulleys

Different pulley belt types were considered, such as miniature geared belts (1) and belts with two lugs fitting into corresponding holes within the pulley wheels (2). Crossed belts were also sketched (3), however, these were rejected on the grounds of introducing possible assembly errors. It was considered that a simple continuous belt, such as that shown in sketch (2) would be the most appropriate for prototype manufacture.

Sketch (4) shows projections from each axle labelled distal and proximal carpal row. This sketch and sketch (5) investigate the possibility of producing axle covers to the rotating sections corresponding to the outline form of the proximal and distal rows. Axle covers were proposed to present a smooth face for the passage of tendons over the wrist mechanism. Sketch (6) indicates that in a similar way to the anatomy the main connection between the wrist and forearm should be through the analogous radius bone (Norkin and Levangie 1992).



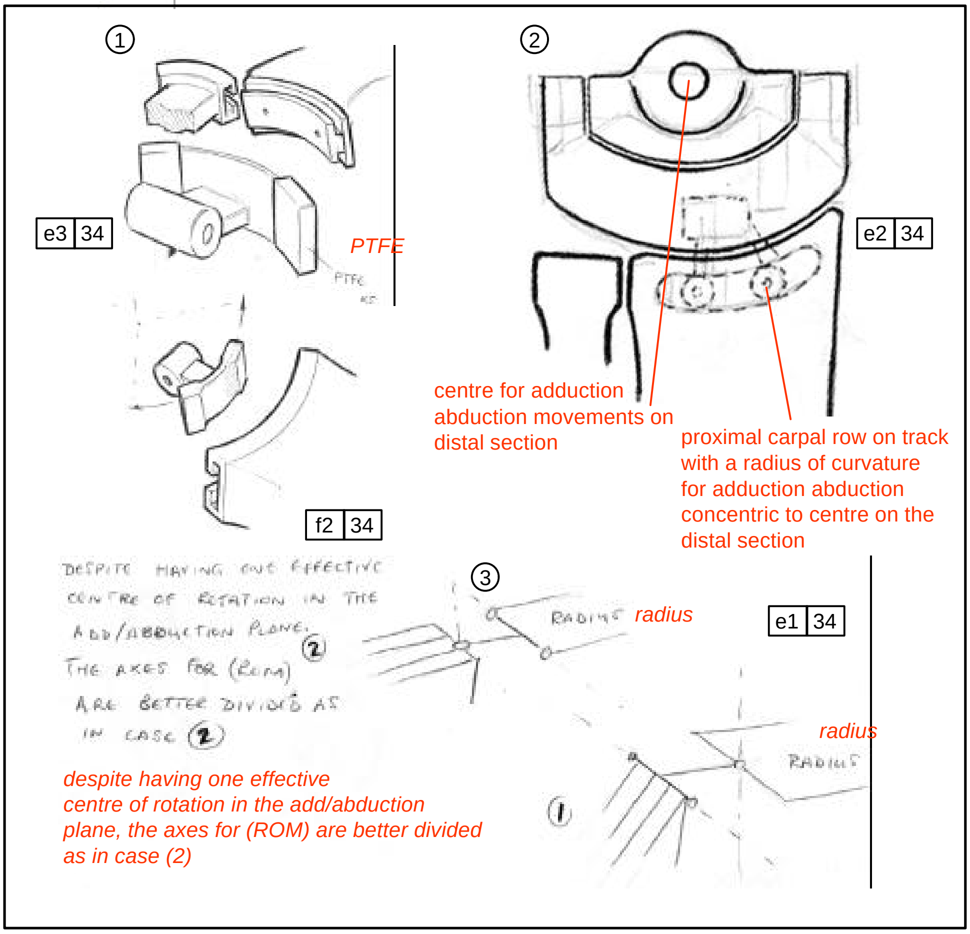
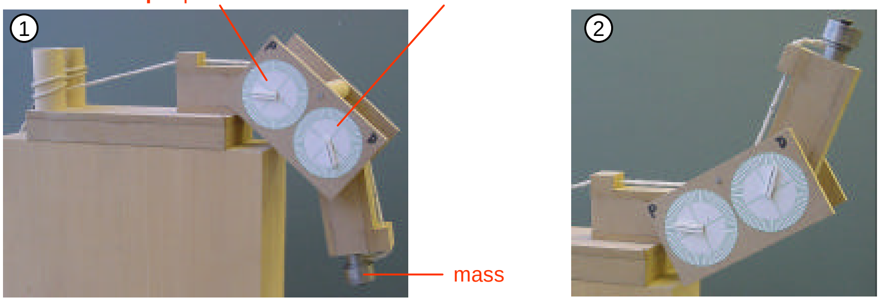
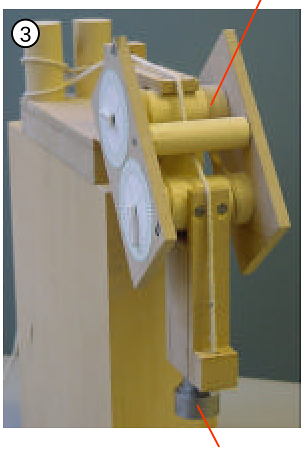


Fig 7.11 Initial Design Ideas for Adduction and Abduction Movements

Progressing from Kapandji's theories of wrist flexion / extension, ideas were developed for mechanical structures combining these articulations with articulations that would permit movement in the plane of adduction / abduction. The simplified sketch depicted in figure 7.8 (2a) indicates that whilst the distal and proximal rows may move independently during adduction and abduction, they still appear to rotate about a single point at the centre of the capitate, a view supported in the literature (Kapandji 1982, Youm and Flatt 1980). Therefore, sketch ideas were produced of mechanical arrangements permitting the fixture of the proximal axle to rotate about this point (1, 2). It was initially proposed that this would be achieved using a curved track possessing a radius of curvature concentric with centre point on the distal carpal row (1, 2). However, further sketch investigation indicated that such a mechanism would allow adduction and abduction of the wrist when it was maximally flexed or extended (3). From palpation this did not appear to occur. Instead it appeared that the plane of adduction abduction, although diminishing, appeared to follow the frontal plane of the hand as it is flexed and extended. Literature on the tendon routing corresponding to the muscles chiefly involved in wrist movement (flexor carpi ulnaris, flexor carpi radialis, extensor carpi ulnaris and extensor carpi radialis longus and brevis) (Smith et al 1996, Lamb et al 1989) appeared to support this reasoning. Therefore, it was concluded that the distal carpal section, following the frontal plane of the hand, should be the only section with an articulation for adduction / abduction movements.





1. no added mass		**2**. 62g mass		**3**. 612g mass	
p (deg)	**d** (deg)	**p** (deg)	**d** (deg)	**p** (deg)	**d** (deg)
5.0	5.0	5.0	5.0	5	2.5
10.0	10.0	10.0	10.0	10	2.5
15.0	15.0	15.0	15.0	15	2.5
20.0	20.0	20.0	20.0	20	2.5
25.0	25.0	25.0	22.5	25	2.5
30.0	30.0	30.0	27.5	30	2.5
35.0	35.0	35.0	32.5	35	2.5
40.0	40.0	40.0	37.5	40	2.5
45.0	45.0	45.0	42.5	45	5.0

Fig 7.12 Testing the Linkage of Distal and Proximal Wrist Axles

At this stage it was considered that mechanical joint principles had been derived for both flexion / extension and abduction / adduction movements. However, it was unclear how the proposed coupled flexion / extension mechanism would behave during actuation from extrinsic tendons; and supporting weight on its distal section. Therefore, a scale model of the mechanism was made with angle indicators connected to each axle. The proposed coupling mechanism worked on equally sized pulleys, therefore similar rotations were expected on each dial as the tendon was pulled.

The test-rig was made from wood. The pulley belts were stout elastic bands, and the tendons were cotton string.

On pulling the tendon, with no mass attached to the distal section, the dials read approximately similar rotations. However, on increasing mass, rotations on the distal section became greater. It was observed that this was occurring due to extension of the elastic band pulley belt. It was reasoned that this was due to the moment between the mass and the distal axle being less than the moment to the proximal axle. It was thought that an analogous wrist exhibiting this behaviour may not be advantageous from both functional and cosmetic perspectives.

It was evident at this stage that to produce a suitable coupled mechanism for wrist flexion and extension movements would require significant further development. Therefore, it was thought appropriate to review the movements of the intact human wrist to ensure that a simple uniaxial articulation was not in fact appropriate.

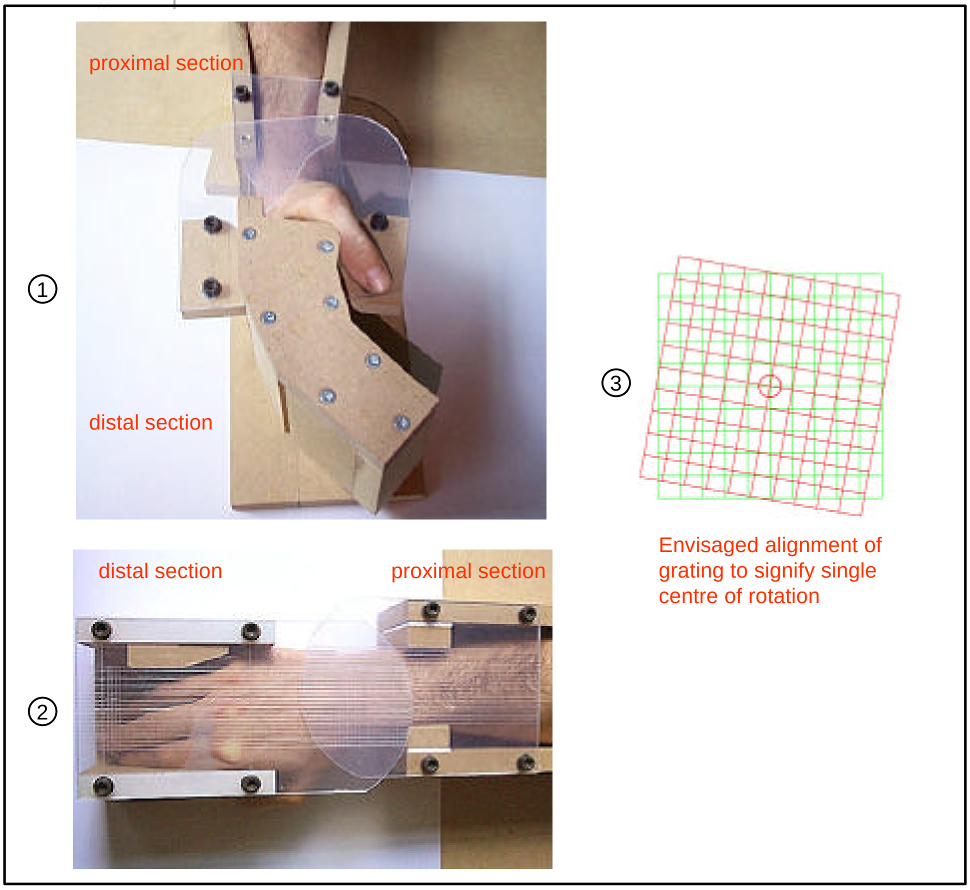


Fig 7.13 Splint Tests to Examine the Movement of a Human Wrist

To examine the movement of an intact wrist, closely fitting wooden splints were made to fit onto one of the researcher's hands. The splints were devised to have a flat base through which the proximal splint was rigidly attached to a wooden board, whilst the distal section could be freely translate on the board. This was done to limit the movement of the joint to a single plane for analysis. Two sets of splints were devised. One to capture movement of the wrist in the plane of flexion/ extension(1), and a second to capture movement in the plane of adduction / abduction (2).

Initial tests were performed to determine whether a single centre of rotation could be located during movements of the wrist. This was done by fixing transparent acrylic sheets marked with grid lines to the proximal and distal sections. It was envisaged that if a single centre of rotation existed for either movement then this could be seen in alignment of grid lines (3). The researcher slowly moved his wrist from maximum adduction to maximum abduction, while an observer looked for apparent alignment of the grids. It was found that the grids did appear to align on a single point in the mid-range of adduction and abduction movements. This apparent centre was marked on the proximal arcylic grid. However it was found towards the extents of movement this marked centre would change.

Although in the mid-range of adduction / abduction movements an apparent single centre could be found, no single centre of rotation could be determined in any part of the wrist movement in the plane of flexion and extension.

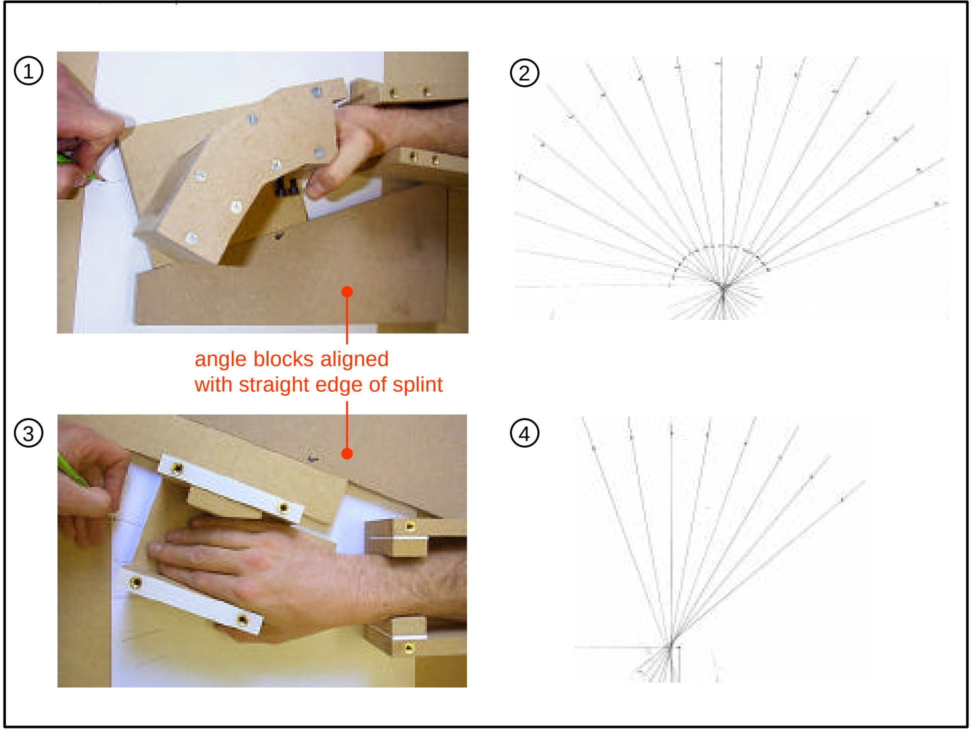
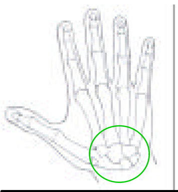


Fig 7.14 Wrist Adduction Abduction Articulation

The absence of a single centre of rotation indicated that the articulation of the wrist in this plane was more complex than a simple uniaxial joint. To ascertain what type of articulation was being demonstrated it was thought appropriate to use a visual method.

Reference marks were placed on the distal splints (1 and 3) and cartridge paper placed under them. Using blocks angled at 10 degree increments marks were made on the cartridge paper corresponding to the reference mark on each distal splint. This procedure was followed multiple times for both the flexion / extension and adduction / abduction splints.

The marks on the cartridge were then scribed through with an adjustable set square. The resulting loci (2 and 4) produced were then examined.



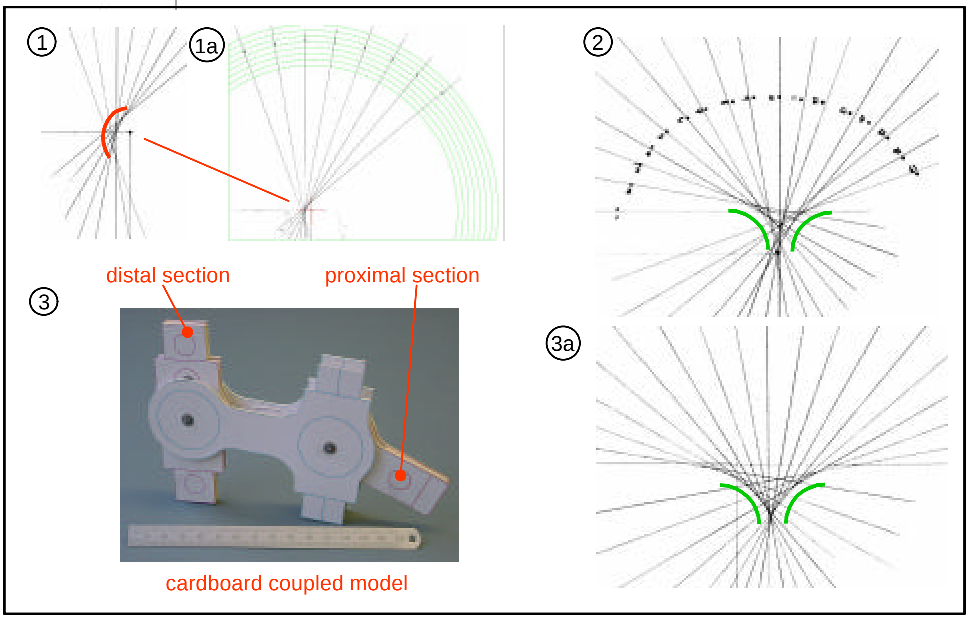
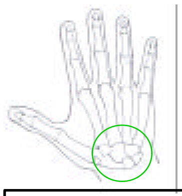


Fig 7.15 Analysis of the Splint Produced Loci

The loci of points that was produced by the splint in the plane of adduction / abduction is shown in figure 7.14 (1). It was expected that the scribed lines would all terminate at a single point indicating a single centre of rotation movement in this plane. However, figure 7.14 (1) shows that the lines do not terminate in a single point. It was reasoned that these lines still indicate a single centre of rotation, only the reference mark on the splint was slightly to the left of the true centre of the joint. This evident as a single arc loci was produced (1). The approximate centre of the marked points was found using a transparent overlay marked with a centre point together with corresponding narrowly spaced concentric arcs (1a). The overlay was manoeuvred over the sheet of recordings to ensure the best fit of the arc of points between the narrow lines. The position of the centre was then marked on the sheet of recordings. The position of these marked centres appeared similar between recordings. Subsequently, this centre position was marked on the board relative to the proximal splint.

Similar recording were taken for flexion / extension movements (2). Unlike the recordings for the plane of flexion / extension, the absence of a single termination of the scribed lines didn't appear consistent with splint misalignment. It was reasoned that for the near 180 degree movement constant misalignment from a single centre would be evident as a single arc, similar but with a more complete circumference to that seen in the previous recordings (1a). However, the recordings showed two mirrored arcs (2).

Concurrently, measurements were taken from anatomical skeletal models to develop a simple scale model of a possible mechanism to approximate the coupled movements of the distal and proximal carpal rows (3). The proximal part of this was secured to a board whilst a straight edge was fixed to the mobile distal section. A procedure was followed similar to that used with the splints to record the locus shown in figure 9.14 (4). It clearly shows the characteristic mirrored arcs that was evident in the flexion / extension splint recordings.



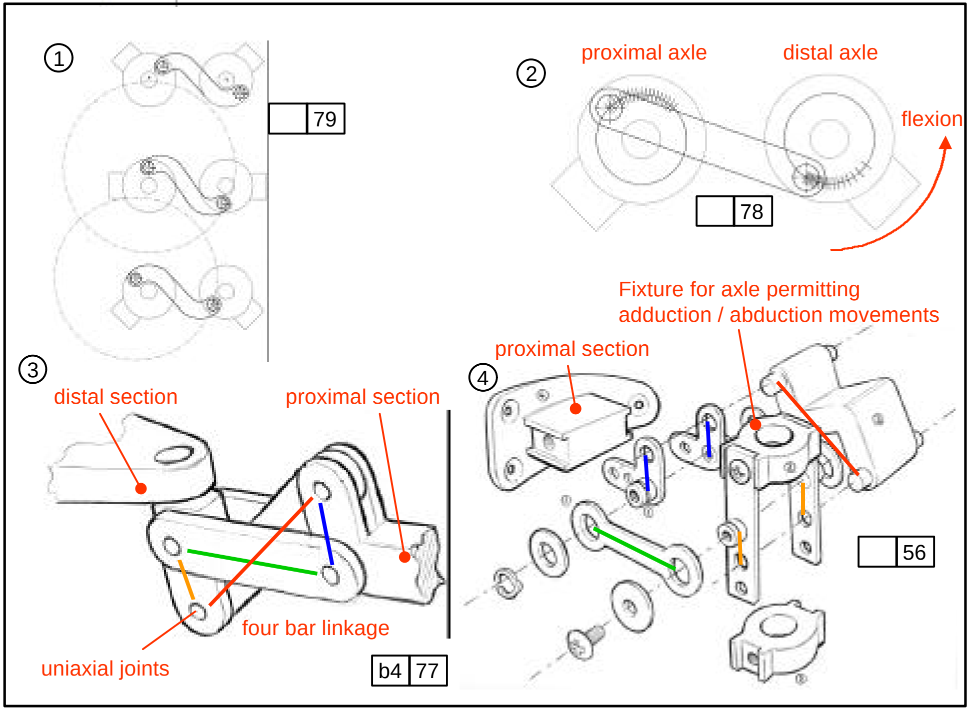
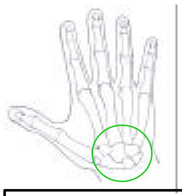


Fig 7.16 Initial Sketches for Rigid Axle Coupling

The comparison of the loci recorded in the plane of flexion / extension for both the human wrist and the coupled cardboard model indicated that a coupled twin axle design might be appropriate.

Initially, couplings had been considered that relied on miniature pulley belts. However, it had been found that these might be vulnerable to stretching with an added distal load. Consequently, it was thought that the coupling of the axles should be simpler and more robust. The simplest coupling of the axles was considered to be a single rigid link (1). Initially, sketch ideas (1) were proposed that retained the historical cylindrical forms that had been necessary for the function of the the pulley system. Using CAD software the proposed coupling of the distal and proximal axles via this link were investigated (1). It was found that by using a scrolled link the distal section could be made to rotate the necessary 180 degrees to approximate the range of movement of a wrist in flexion / extension (Kapandji 1982). However, during this process it was found that rotation of the distal and proximal axles did not appear to be exactly matched unlike the pulley system. This was further investigated by marking the necessary arc of movement on the proximal section in 5 degree increments. The corresponding position of the link on the distal axle was then marked. It was evident from this exercise that the relative increment of movement on the distal section increased as flexion increases (2). The simple model that had been used to produce the recordings that were compared with the recordings of human wrist had been linked in this simple manner. Therefore, it was reasoned that this type of coupling might in fact be appropriate.

It was realised at this stage that the essence of the proposed mechanism relied on four bars being linked through simple uniaxial joints (3). Therefore, designs were proposed that dispensed with the previous cylindrical forms. Focus shifted to combining the four bar link mechanism with an axle on the distal section that would permit adduction / abduction movements of the hand (4).



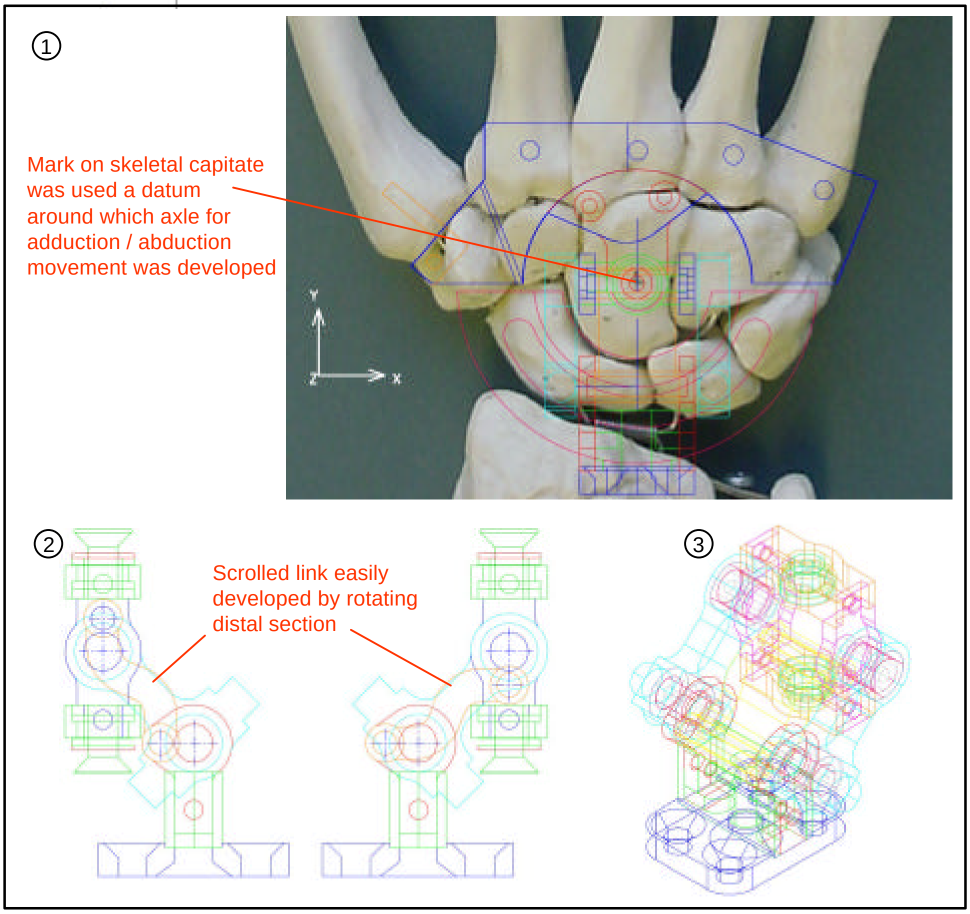


Fig 7.17 CAD joint development

Much of the previous joint development had progressed through sketchbook idea development. However, it was considered that both due to the small scale and the multi-articulate nature of the proposed design that further development would be more appropriate using CAD software.

Although the simple model had shown similar characteristics to those of the wrist, the four bar link mechanism is quite unlike the boney and ligamentous structures of the human carpus (Kapandji 1982). Therefore, extensive development work was needed to detail the dimensions of the mechanism to fit within the volume of the human skeletal carpus. As an aid to development, photographs of the skeletal carpus were used as backgrounds on the CAD screen (1). Using CAD software it was found easier to develop the forms of the links necessary and ensure the correct interference free range of movement of the mechanism. Figure 7.18 (2) shows the scrolled link in gold, the development of the shape of this link was aided by being able to easily rotate the distal section. The dimensions used for the links involved in the flexion / extension mechanism came from measurements of the diameters of the lunate and capitate from skeletal anatomical models.

Anatomical literature indicated wrist movements could be considered as occurring about a centre approximately at the middle of the capitate (Youm and Flatt 1980, Kapandji 1982). This appeared consistent with the recordings from the splints. Therefore, a mark was placed on the skeletal capitate (used as the CAD background) and this was used as the datum around which the articulation for the adduction / abduction mechanism was developed (1).

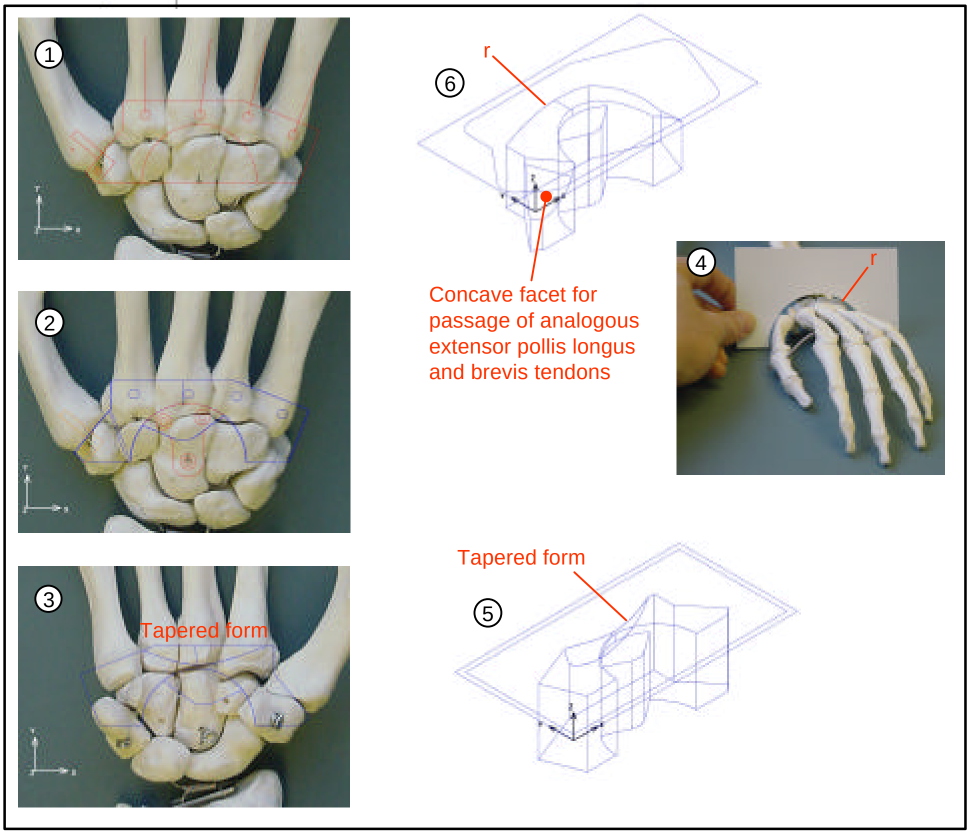


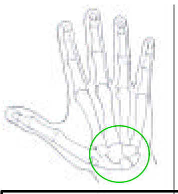
Fig 7.18 Development and Investigation of Joint Form

In the development of the linkage mechanism the carpal bones were treated as distal and proximal rows. The carpal bones were similarly treated as fused 'rows' in developing a form suitable to act as an anchors for the digits. The distal row needs to secure the metacarpal shafts at the correct angle and spacing. The angles and spacings were determined using CAD software underlayed with a photograph of a skeletal hand (1).

The outline plan of the model distal carpal row was determined by simplifying the outline of the trapezium, trapezoid, capitate and hamate carpal bones. Additionally, the proximal face of the form was shaped to allow a range of movement in adduction/abduction for the linkage mechanism similar to that determined using the splints (2). This was achieved by rotating the previously designed linkage mechanism about the centre of the capitate. Kapandji suggests that this can be considered as the centre of wrist rotation in the plane of adduction and abduction (Kapandji 1982), which appeared consistent with the position of the centre of rotation found using the splints.

The form of the human skeletal carpus was investigated in the tranverse plain using profile guides. Differently radiused profile guides were made to determine the approximate radius best fitting the dorsal arch of the carpal bones (4). The proximal form of the metacarpal shafts appeared to be tapered into the carpals (3), therefore, a taper was introduced into the volar side of the form (5).

The previous model hand showed problems routing analogous extensor pollis longus and brevis tendons. Using the described underlay and profile guide methods a the form of a concave facet was determined and included in the computer 'solid model' (6).



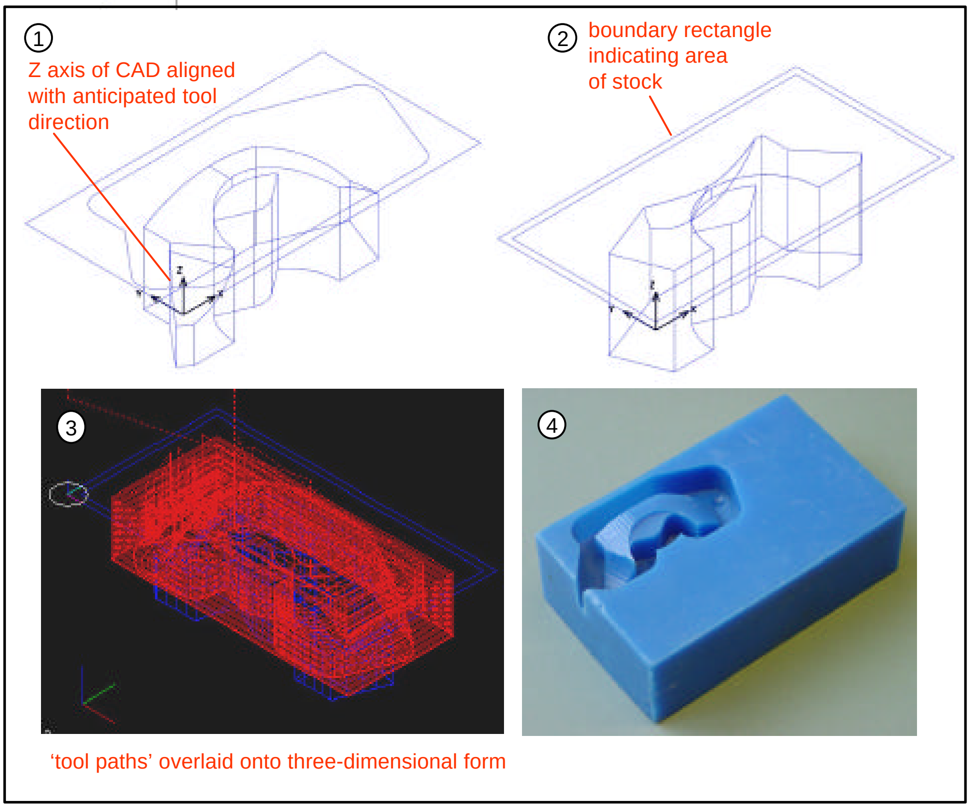


Fig 7.19 Three Dimension Machining of Distal Carpal Form

The details of form from the CAD development work required machining in a 'three-axis' strategy. The machining considerations were included in the development of the CAD solid model, this included orientating the z axis of the solid model with the anticipated tool direction (1). Additionally, a boundary rectangle was included with the global co-ordinates aligned to its bottom left corner (1). This rectangle represented the stock which the form was to be machined from, with the negative z direction indicating removal of stock.

The computer aided machining software (CAM) was able to automatically create tool paths resulting in a form requiring minimal manual finishing (3). Figure 7.19 (4) shows the tool paths tangibly tested in an easily machined block of wax.

The chosen material for the distal carpal row was a lightweight bearing plastic, similar to that used in the first model hand. This was chosen as analogous tendons will run across this component, favouring a low friction material.

The design requires holes outside the plane of the machined surface features. Therefore, once the stock was machined to size the holes were machined using a manual milling machine. The stock was then transferred to a CNC milling machine. Four sides of the stock were used as datum faces. Three corresponding to the initial position of the origin x,y,z. One side of the design was machined then removed from the vice. The resulting machined 'pocket' of the partially machined form was refilled using a soft polyurethane two part casting plastic. This was skimmed then replaced into the vice jaws to the to be at the underside of the stock. The polyurethane served to hold the highly contoured form whilst the second side was machined. This material was subsequently easily parted from the desired component.

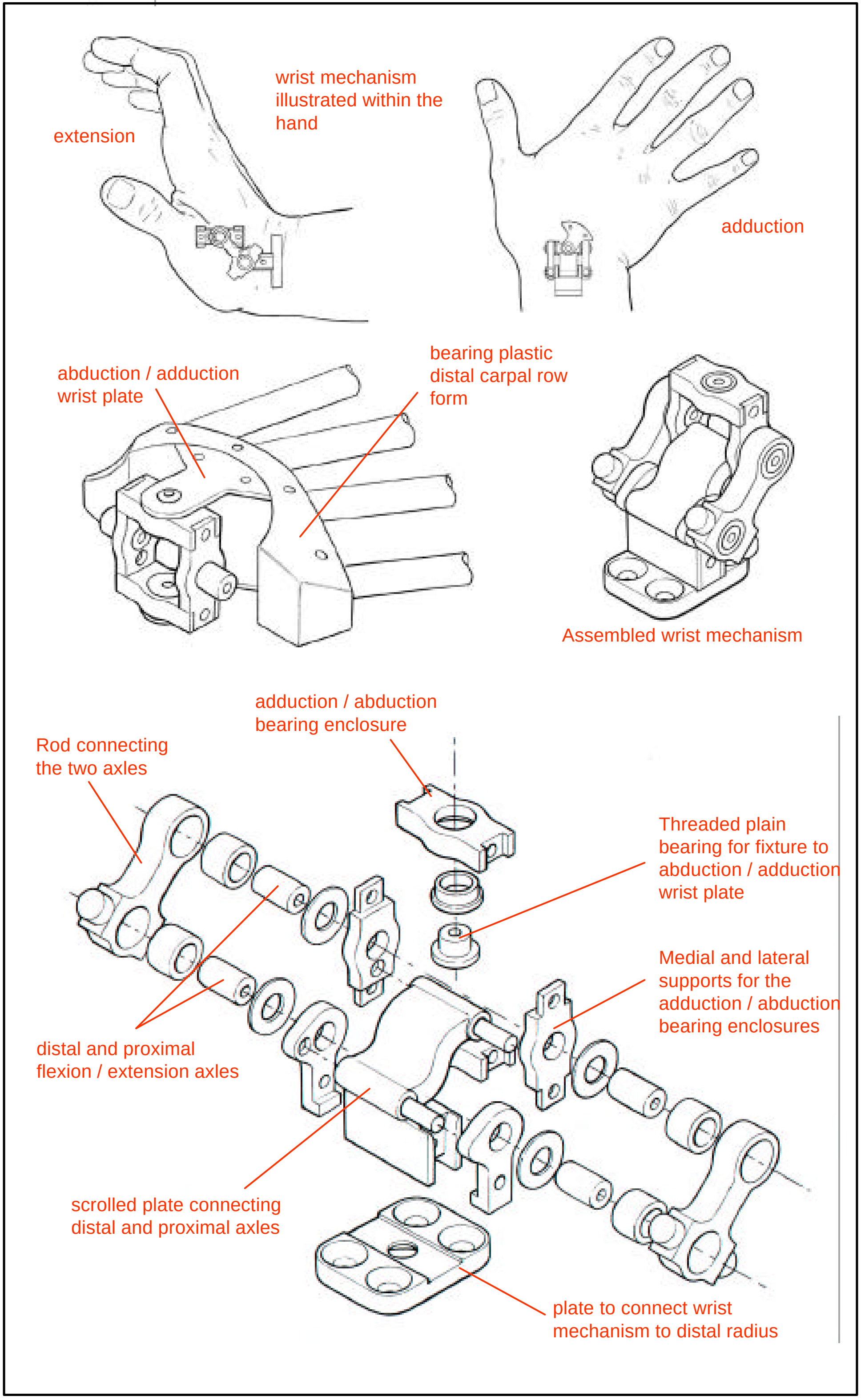
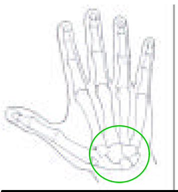


Fig 7.20 Principles Embodied Within the Model Wrist Joint

The diagram above shows the model wrist mechanism along with indications for the principles embodied within its design.



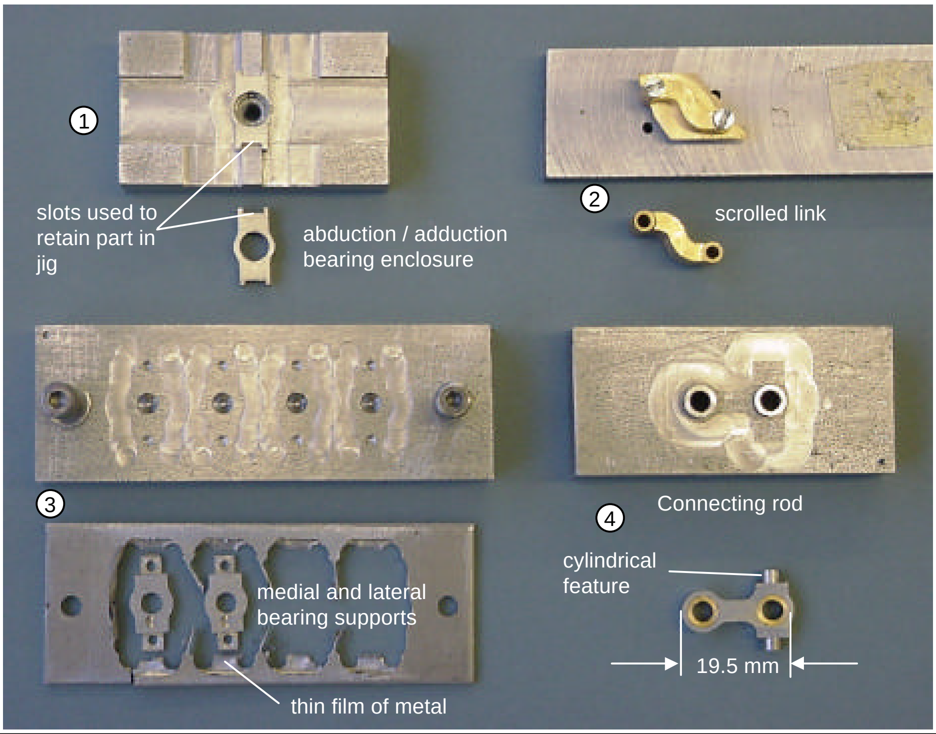


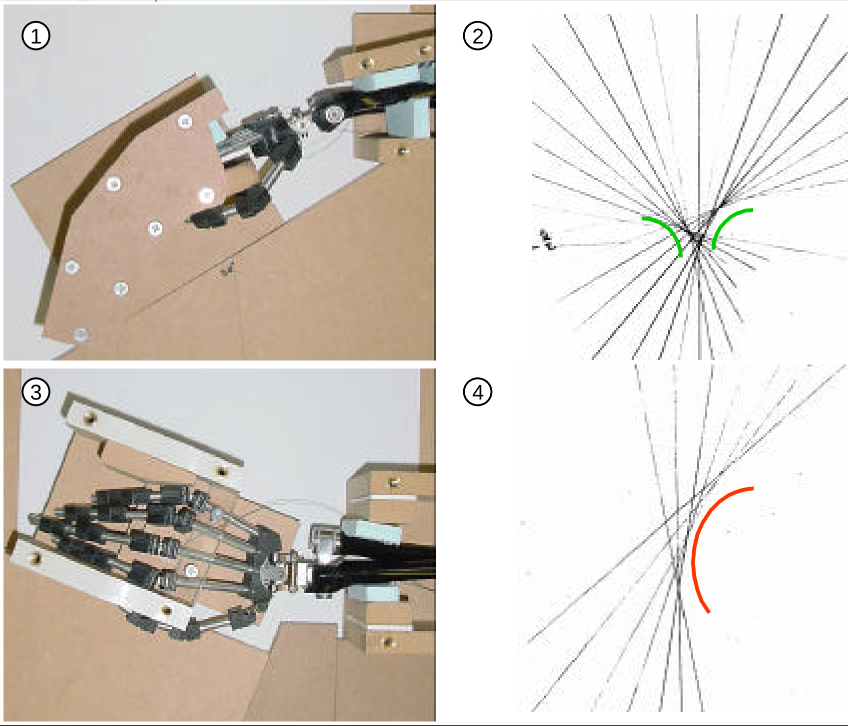
Fig 7.21 Jigs Used during Manufacture of Small Wrist Components

The forms developed for the linkage mechanism needed to be of a miniature scale to fit within the volume occupied by the human carpal bones, consequently, the longest component was only 19.5 mm. However, the coupled pulley experiment indicated that the components would need to be rigid to maintain the correct movement characteristics. Consequently, mild steel was chosen as the prototyping material.

Due to the small scale of the components, conventional vices and fixtures were unsuitable, therefore, several holding jigs were machined. The miniature adduction / abduction bearing enclosure was made by first machining slots in the sides and drilling the various holes. The slots were then used to locate the component on a steel jig, and secured through the central hole using a machine screw. The final profile was then machined onto the sides of the part (1). The scrolled crank was prototyped in hard brass for its bearing properties. The brass stock was first drilled. A steel jig was made with four holes corresponding to the position of the scroll in mirrored positions. The brass stock was roughly cut to length and secured with machine screws to the jig. Half the depth of the profile was machined, then the scroll was placed on its reverse side and a mirrored profile machined (2).

The more simple distal axle supports were machined in multiples (3). This could be done as the program was designed to leave a small thickness of metal between the parts and the remaining stock to maintain the location of the parts throughout the machining sequence. The thin metal film was subsequently easily cut to free the components.

The connecting rod between the distal and proximal axles required a cylindrical features machining in plane out of plane to that of its the profile (4). These ‘bosses’ were first machined into the sides of a length of correctly ground stock. The stock was then rotated through 90 degrees and the holes machined in this length. Finally the stock was roughly parted to length and the final profile machined in the jig shown (4).



R.O.M (degs)
flex / extension
175.0
175.0
177.0
175.5
human wrist*
170

R.O.M (degs)
add / abduction
63.0
62.5
61.5
62.5
human wrist*
55-60

Fig 7.22 Tests on mechanical Model with using Splints

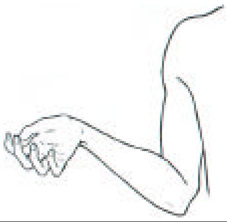
The model wrist was assembled and connected to the model hand, forearm and elbow sections. It was then possible to place the hand within the splints and assess the quality of the movements (1, 3).

As the model is only an analogy of the human wrist at skeletal level it was necessary to place foam block to the sides of the splint to simulate the bulk of soft tissue around the intact human wrist (3). Once this model was secure within the splints similar procedures to those followed to produce the recordings of incremental movement.

The recordings appear close to those of the intact human wrist. There appears to be a single centre of rotation in the plane adduction / abduction (4). Whilst the four bar link characteristics are evident in the recording for flexion and extension (2). However, difficulty was found in securing the skeletal model into the space previously occupied by the bulk of an intact hand.

Due to the lack of soft tissue surrounding the wrist and forearm it was difficult assess the range of wrist movement using goniometric techniques. Therefore, the splints were used to calculate the range of movement of this joint, shown in comparison to human wrist (*Kapandji 1982) in table 1. However, difficulty was also experienced in securing the skeletal model into the splints designed for the intact human hand.

Whilst these results were promising it was felt that further qualitative evaluation was needed to ascertain whether the subtle differences in wrist mechanism added to the closeness of the anatomical analogy. It was considered that to obtain a valid qualitative evaluation of the wrist joint it was necessary for the limb to be complete with hand and elbow; so that the form of the model would appear somewhat familiar to the person asked to evaluate the joint.



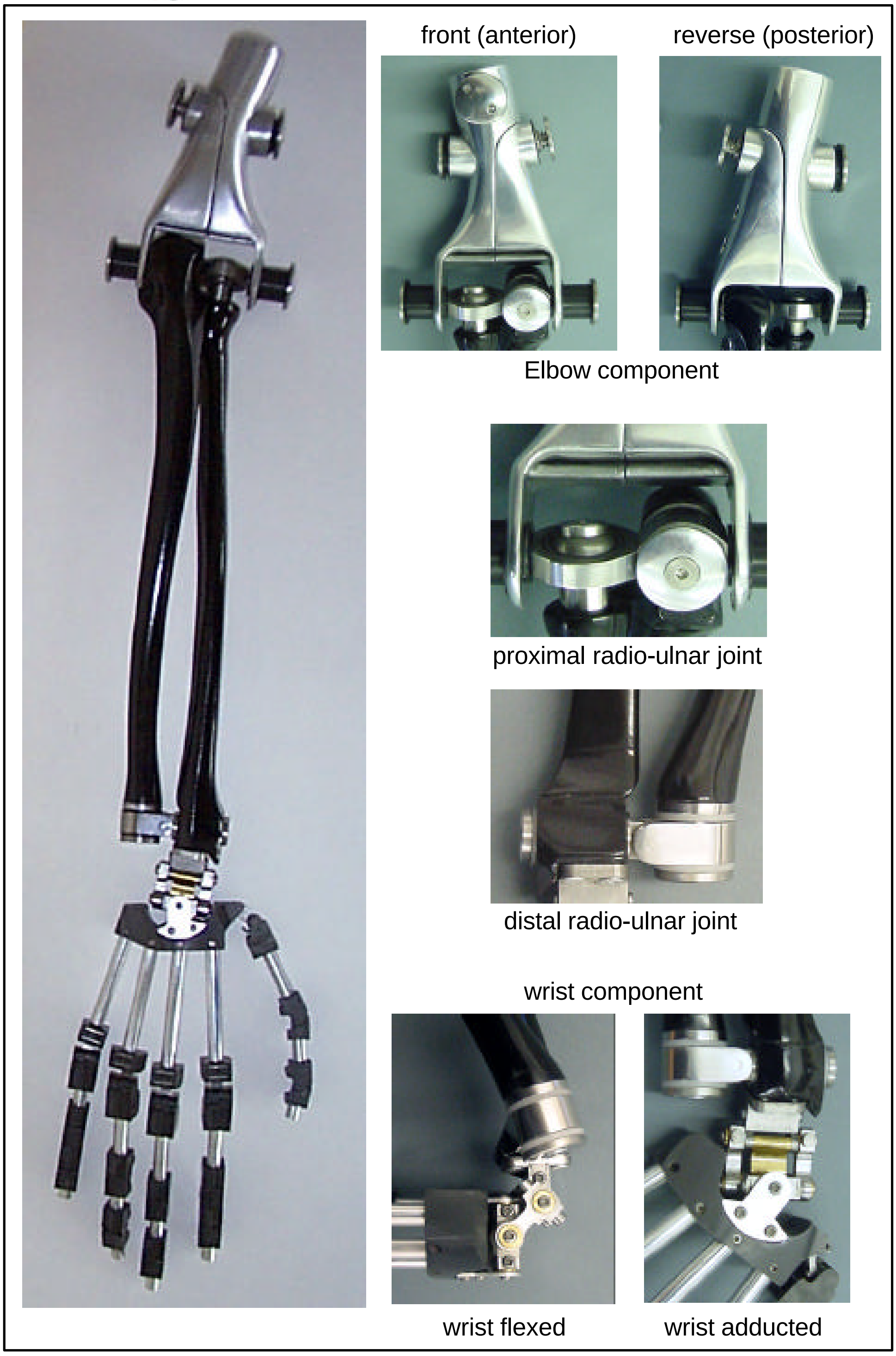
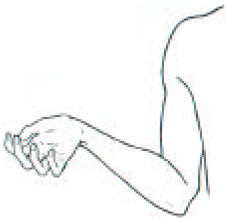


Fig 7.23 Components of the Assembled Skeletal Model Arm

Once the model limb was complete, with new components for wrist, forearm and elbow and the earlier finger joints retained, it was thought appropriate to submit the model limb for qualitative evaluation. This was done for two reasons. To determine whether the joints were achieving a close analogy of the human limb. In addition, a key prosthetics researcher was presented with the limb for evaluation to determine if any of the principles embodied in the model were appropriate to the field of prosthetics.



Qualitative Evaluation by Lisa Halse, Osteopath

Lisa Halse is an osteopath in Sheffield. She was invited to evaluate the model wrist elbow and forearm. She was selected as she routinely uses palpation of intact limbs as part of diagnosis, and therefore was considered to have a keen sense of what the articulations human limb should feel like. The aims of the evaluation were for L. Halse to indicate from palpation where deviations from the original anatomy appeared to arise. During the evaluation L. Halse was encouraged to mark the model arm with adhesive paper markers where she considered the model to diverted from the original anatomy. The interview took place in the research workshops at Sheffield Hallam University. Present were L. Halse, R. Erol, C. Rust and G. Whiteley. The evaluation lasted for approximately 45 minutes.

Her initial views of the model arm were noted down as very positive, commenting that she was very impressed by it and had never seen anything like it before.
The remainder of the interview with L. Halse was tape recorded. Below are the salient points she made, together with quotes from the transcript of the interview.

(1) L. Halse carefully palpated the model forearm in pronation and supination movements commenting:

'It's definitely mechanical…there's no sense of …things receding and coming back….It's <requires> a sort of springiness of a kind.'

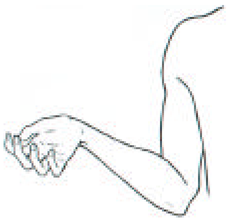
(2) L. Halse contrasted the model to the human forearm indicating the absence of soft tissue within the model was hampering her evaluation

'…you can feel if it's <original anatomy> alive..you can feel there's a sort of slight expansion, or rotation and contraction sort of feel to the tissue.'<considered absent in the model>

(3) Both the original model wrist and the current model wrist were presented to L. Halse for palpation. Her first palpation was of the current wrist joint.

'It's incredibly mobile…it's definitely in need of some attachments (muscular constraints)'

'This <current model wrist> is definitely better than the joint you've got there <original model wrist>. This feels basically a lot lighter. That one <original model wrist> feels much more mechanical. You get a real kind of end stop, as opposed to this one, which feels like..yeah there is a kind of end stop but it doesn't feel quite so clumsy.'



Evaluation by Lisa Halse Continued

(4) L. Halse considered that although current model wrist possessed the range of movement of the anatomical carpus, she felt that more flexibility was required in its form permitting transverse flexibility across its arch.

'…I think you need to do something about getting more flexibility across the arch…there is a degree of flexibility between the carpals and the metacarpals'
'..normally when you put your thumb out there like that <adducted and extended>…you spread the carpals, and it's almost like you want some…elastic tissue in it or something … to compress, but will spring back.'

'I think the springiness is important….in order to make it feel like a real hand it needs something less rigid.'

'..make it more elastic…then you'll get some of the shock absorbence that you don't get in this material <indicates metallic sections>'
'if anyone was to fall on this thing <current model wrist> in extension it's just going to go <demonstrates impact going right up through the arm>'

(5) On picking up the model for palpation L. Halse commented on the difference in weight between proximal and distal sections of the model.

'It's massively heavy <model elbow> … it won't integrate <with the movement of the amputees body> while it's got this massively heavy joint.'

(6) L. Halse was content with the quality and range of movement of the model elbow being close to the original anatomy. However, throughout her palpation of the elbow L. Halse indicated that the sinuous form of the model elbow aided the analogy to the original anatomy.

'…the kind of movement through, and feel of it,…it feels like its much more alive.'
'It's the form, because of the curve this way, and the curve that way, and it's rounded.'

(7) L. Halse indentified that there was a need to review the form and dimensions of the epicondyles on the model elbow.

'The lateral one <humeral epicondyle> is a lot smaller than the other one <medial humeral epicondyle>…you look at that elbow <model elbow> and you think well visually…this is much too wide <width between epicondyles>'

(8) L. Halse considered that the model 'origin' Brachioradialis was currently in the wrong position, and may be of an inappropriate form.

'…it's not like when you look at an anatomical text book and it has a little red dot saying that's where it is, it is not as clear as that…it's covering <origin of brachioradialis> quite an area rather than just a little point…It's much more ..of a line, it's not a spot…I'd say it was way to... high <proximal> for brachioradialis '

Evaluation by Lisa Halse Continued

(9) L. Halse palpated the finger joints and was content with the ranges of movement of the IP joints, but, commented that the model MCP joint was;

'..Incredibly mobile…. it's double jointed…'

However, L. Halse was concerned that the form of the joints too mechanistic.

'...This hand is very strange because its not got its arches <indicates absence of longitudinal arch of plalanges>'
'…It's the form <cubic form of model finger joints>….this is sticking into my hand going jab, jab, jab'

(10) L. Halse indicated at several points that the lack of soft tissue within the model was hampering the close analogy of the model to the original anatomy.

'…you've got to build on <to the model> some muscle..'

'..if you start putting on something..elastic,..you know something that can conform into that function <indicated contracted muscle of forearm> …and it has elasticity to go back again,..you can start building up soft tissue in the model it will feel more real..'

'It's brilliant, but it's nothing like a real hand because it's got no soft tissue'

(11) She additionally felt that the absence of soft tissue was hampering her evaluation of the model

'…I want it to have all the rest of the soft tissue on…, to feel'

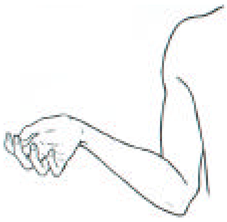
(12) L. Halse was enthusiastic about the methodology used and hoped to be consulted again when more practical progress had been made.

'…your trying to do something…which is great…a huge improvement on what's been done before.'

'..it's brilliant…'

'I'd love to come back and see how it's going.'

The evaluation concluded by L. Halse expressing a desire to review the model again when more progress had been made towards analogies of the soft tissues of the limb.



Evaluation by D. Gow, Biomedical Engineer at Princess Margaret Rose Orthopaedic Hospital

D. Gow is a biomedical engineer and a key figure in the design of new prostheses. He and his colleagues have designed and prototyped the widely publicised multi-articulate upper-limb prosthesis based on the ‘pro-digits’ concept (containing the actuating electric motor within the volume of the finger).

The evaluation of the model took place in D. Gow’s office at the Princess Margaret Rose Orthopaedic Hospital. Present were D. Gow and G. Whiteley. The evaluation lasted approximately 45 minutes and was taped recorded. Before D. Gow was presented with the model an outline of the research aims were given by G. Whiteley. Salient points from this evaluation are presented below using quotes from the transcribed tape recording.

(1) D. Gow’s Initial Remarks

‘It’s <the model> sort of an engineering challenge…taking that from an inert skeleton to a powered and controlled device…It would take us a generation I think.’

(However, D. Gow expressed an interest in the details of the design of the model limb for practical shorter term utilisation. Particularly in the joints of the model hand).

(2) The Model Finger Joints.

‘Yeah that’s very, very impressive….you are sort of producing the bits that are actually important, because these..you know the joints…<points to finger joints> nobody as far as I’m aware in prosthetics or robotics has really come up with a simple machinable system that gives you the anatomical equivalents.’

(3) Anthropomorphic Joints supporting Functionality

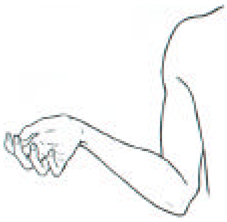
‘…the attitude of the hand becomes an issue because a flat hand isn’t much use for prehension…hence the compromised grip that most prostheses have. So again a device where you can alter the the attitude of the thumb, even passively, to give opposition and...lateral pinch or...the power grip. Again I think that would be a commercial breakthrough.’

(4) Anthropomorphic Joints supporting Passive Cosmesis

‘I think that in certainly in the sense of a passive device while it may be attractive to have that form of movement <adduction / abduction at the MCP joint> it just depends how you protect that from being damaged.’

(5) Using the Model as the Basis for a Body-Powered Device

‘…basically I don’t see how difficult it would be to produce a voluntary closing hand with this..<model hand>’



David Gow Evaluation continued

(6) Modularity of the Joints Supporting Economic Manufacture

'The attraction to me is if this < the model limb> brings any spin-offs in the sense that our own work has done which is to start looking at all of this thing as a modular system…once you start saying you've got a system…you start ringing bells about cost. Cost coming down in terms of bulk manufacture.'

'…if I can get a hand...made up of virtually the same parts just with or without power sources then probably I've produced something I can make in quantities that are four or five times greater than the moment…..that would mean that some of parts are made in almost economical quantities…'

'on this…system where you had certain joint lengths and segment sizes for different hand sizes and left and right hands you can immediately see a production engineering approach to it.'

'..if I could produce a skeleton like this …you'd start to interest manufacturers in terms of injection moulding ….you'd start to produce economic quantities of these things.'

'In essence this has to cost something like 20 quid to make. And you could just about imagine a system based on joints like that <indicates model finger joints>. Because the joints have got similar form..'

(7) Further Develpemnt from Elements the Model's Design

'This <the model limb> interests me from the perspective that the challenge of this is to see this as more than just a design exercise, mimicking the human body , but taking elements of this and making them practical from a prosthetics point of view.'

'So things the that I can see that are immediately attractive to me are; that a skeletal hand system like this would potentially be able to be used within a cosmetic sense.'

'..this <model hand> I could see us making that fit a silicone glove as it is…'

'…that's really quite an exciting concept to see that hand <the model hand> start there with effectively rigid and strong mechanical phalanges …and to have some sort of articulating system beyond the metacarpophalangeals.'

(8) Chief Constraints on Prosthetic Technology

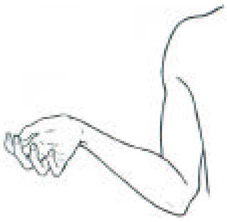
'…from a prosthetic point of view what holds prosthetics back is the need for simplicity and reliability and cheapness…'

'…. the prosthetics industry is so small and so driven by the need to make their next step incremental…'

' You don't get the desire to leap forward <in the prosthetics industry> with this <indicates model limb> because no one can afford the outcomes>'

(9) Articulations Supporting Human Movement (Dynamic Cosmesis)

'….technology that we've currently got is now getting interested in this <points to model arm>, is getting interested in articulation. Because the patient, the human element, dictates that people get the benefit of better dynamic cosmesis'.

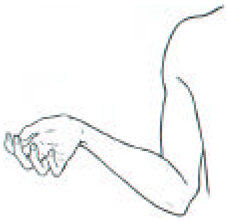


David Gow Evaluation continued

(10) Comments on existing technology

'….my feeling is that the technology that we've got is akin to the stone age…'

This evaluation of the model was followed by discussions with both D. Gow and his colleagues in the research work shops at Princes Margaret Rose Orthopaedic Hospital. D. Gow indicated that he would like to be kept in contact with the progress of the research. He also requested a replica of the joints of the model hand to experiment with.



Qualitative Evaluation by Professor Jon Stanley, Orthopaedic Surgeon University of Manchester

After evaluating the model forearm D. Stanley was informed of the subsequent plans the research had to design an anatomically analogous wrist joint. D. Stanley asked to be contacted when this was complete, as he thought Professor J. Stanley, one of his fellow surgeons, and respected authority on the anatomy of the human wrist would be appropriate to evaluate the model wrist.

The evaluation by Prof. J. Stanley took place at Northern General Hospital, Sheffield. Present were Professor J. Stanley, D. Stanley, G. Whiteley and C. Rust. The evaluation lasted approximately 30 minutes, and was tape recorded.

Before Prof. Stanley was presented with the model arm to palpate the brief aims of the research were given. The aim of the evaluation was stated to inform the researcher where the model appeared close to the anatomy, and where it was viewed to divert from the anatomy. Although Prof. Stanley was specifically contacted to evaluate the wrist, his comments encompassed all the analogous joints.

(1) Initial Remarks

'I mean it's absolutely super, really beautiful.'

(2) Regarding the Degrees of Rotational Freedom of the Human Wrist

'It has three degrees of freedom, not two..<like the model wrist>…Which is longitudinal rotation…it's not very much, it only has to be about 20 degrees.'

'If you could put another <degree of rotation>…I'm just wondering where you could put it …it's not much, but you can actually fix the wrist and rotate the hand.'

(3) Wrist Articulation in the Plane of Adduction / Abduction (Radio-ulnar Deviation)

'As far as the wrist is concerned the radio-ulnar deviation are nicely done, and that's <palpates the model wrist> the right amount of motion.'

(4) Articulation in the Plane of Flexion and Extension

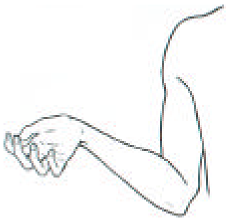
'I can see you've got a beautiful linkage here to shift the axis forward haven't you…It's very nice <comment on movement from palpation>.'

'…no that's beautifully done. I would complement you on that.'

'I'm impressed by the way you've done the linkage for the wrist that is very nice. That really does look normal.'

(5) Overall impression of Wrist Joint

'I would say that the only thing that is missing is just the long axis rotation <at the wrist>. I'm not sure you need very much <movement in this plane>, and I'm sure you could incorporate it into the hand level without disturbing what is basically an extremely nice design. Because it does exactly what a wrist does, it just doesn't rotate <around long axis of the forearm.'



Qualitative Evaluation by Professor Jon Stanley continued

(6) Forearm Joints Reproducing Human Like Movement

‘As far as pronation and supination are concerned, that’s fine <palpates the model> it doesn’t actually work that way. But it’s pretty close…it’s actually reproducing the movement pretty accurately.’

‘…in terms of the net effect, overall it’s pretty good, in fact it’s very good…you’d be hard pressed to tell the difference <between model and human forearm articulation>’

(7) Origins of the Anatomical Mechanism for Forearm Pronation / Supination

‘…the axis of rotation is based on an interosseous membrane it doesn’t work on two fixed linkages.’

(8) Difficulties assessing the model against a human limb.

‘I’m trying <palpates model with eyes shut> to ignore what it looks like and try to see what it does.’

(9) Absence of soft tissues

‘..what you need to do is cover it in a rubber glove or something filled with silicone or saw dust, just to give it that damping effect…’

‘…once you’ve <the researcher> got it powered up and some damping on it, it will be absolutely super.’

The evaluation finished with Professor Stanley indicating that he would like to evaluate the model wrist again when further work had been completed on the models actuation.

Discussion

A discussion of the development of the whole arm is included in the next chapter. Therefore this discussion is focussed on the model wrist joint.

The evaluation of the model hand indicated that the translation of IP joint principles to the wrist joint appeared unsuccessful. In the initial stages of the second cycle of wrist development principles from the development of the MCP joint were translated to the wrist, and again appeared inappropriate. Therefore, it was considered that a stage of creative reasoning was needed for the wrist joint including a stage of extensive observational drawing.

Similar to the development stages in the development of the forearm joints it was found that the creative reasoning process required supplementary techniques. An additional stage of measurement taken form splints was including to further inform the design of the wrist joint. Like the forearm joints an extra stage was necessary as the movement of the intact human joint observed was indicating a complex coupled movement.

The prototyping methods used to develop the wrist included the extensive use of CNC machining. This was both used to create complex forms modelled on the form of the distal carpus, and miniature components for the wrist mechanism. CNC appeared successful both in ensuring the accuracy demanded of miniature components and also the creation of accurate complex forms.

The evaluation of the joint showed again the difficulties of assessing the model against the human limb without soft tissue on the model. This was evident in difficulties experienced fitting the model limb into the splints designed for the intact limb. This was also evident in the transcripts, where evaluators indicated a need for an analogue for soft tissue to add properties such as ‘damping’ to the joints. The evaluations by L. Halse and Prof Stanley highlighted that they the considered the articulation of the model wrist to be close to that of the human wrist. However, L. Halse indicated a need for further inter-carpal articulations and Prof. Stanley indicated a need to include a further limited degree of freedom aligned with the long axis of the forearm.